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MAGNETIC LINEAR ACCELERATOR (MAGLAC) AS DRIVER FOR IMPACT FUSION (IF)

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ABSTRACT

This paper presents considerations on the design of a magnetic linear accelerator suitable as driver for impact fusion. We argue that the proposed approach offers an attractive option to accelerate macroscopic matter to centiluminal velocity suitable to fusion applications. Design and practical engineering considerations are treated. Future work are outlined.

I INTRODUCTION

We advance here a concept and a design of another promising driver which provides a simple match to the inertial target. The ignition is caused by a macroscopic particle (0.1 - 1.0 g) travelling at hypervelocity (sub-relativistic) speeds ($\leq 10^6$ m/s). We shall call this method of fusion by the generic name Impact Fusion (IF), and the driver, Magnetic Linear Accelerator (MAGLAC).

The impact of a fast moving object onto dense matter causes a shock wave accompanied by a severe rise in pressure and temperature. The high pressure, that lasts for a short period of time ($\sim$ 10 ns), is analogous to the high pressure that exists in the core of celestial bodies, where thermonuclear burn is the primary energy source.

This well known process of achieving controlled fusion through direct impact of a projectile has considerable advantages. One of the advantages of this inertial confinement scheme, apart from being of modest cost, is the very simplicity of ignition processes. During impact, a large amount of momentum is delivered onto the target, without a plethora of esoteric processes in which kinetic energy is converted to momentum.

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The basic processes leading to compression are governed by classical hydrodynamics. The fusion target design should then be relatively simple, removing the need for classified complex target designs. Simplicity is also gained in reactor vessel design as its pressure can be maintained at high level. There are no space charge forces which usually limit the high intensities required in e-beam or ion-beam drivers. Since no focussing is required for the hypervelocity projectile, the coupling between the accelerator and the reactor chamber can be isolated except for a small hole (a few mm) for projectile entry. Thus the subsequent shock waves generated by the microexplosion are not expected to cause extensive pertubation to the alignment of accelerator elements. As we shall show in the following, the projectile will be only a few mm in length and diameter. The required input power, 10^{14} W, can be achieved by accelerating the projectile to over 10^5 m/s.

II ACCELERATION OF MACROSCOPIC OBJECTS

The magnetic linear accelerator is the only viable method to accelerate a macroscopic dipole to hypervelocities. Previously methods for accelerating macroscopic projetiles have been proposed or tried. These methods include light gas gun ($< 10^3$ m/s), electrostatic accelerator ($< 10^4$ m/s) and magnetic acceleration of conductive projectiles by a magnetic travelling wave. In the latter scheme, large eddy currents are induced in a highly conductive projectile, conceivably shaped as a torus, thus forming a magnetic moment. The rapidly changing magnetic field of the travelling wave accelerated the magnetic moment along the principal axis. It is shown however that the generation of eddy current will be accomodated by a disastrous joule heating which eventually will evaporate the conductor in flight.

Magnetic acceleration of ferromagnets or ferrites remains a possibly viable scheme. However, as we shall show below it is more difficult to accelerate the projectiles to the required velocity due to the relatively low saturation field strengths of the ferromagnetic materials. A simple approach to avoid the heating problem is the use of superconducting projectiles. A large intrinsic magnetic moment can be acquired by a superconducting solenoid and thereby accelerated by a travelling wave[1,2] Such a device can be shown to have a stable longitudinal acceleration, but it suffers from transverse instabilities which could destroy the trajectory of the projectile due to inevitable transverse drifts during the injection cycle.

Our proposal[3,4] here is to accelerate a superconducting solenoid or a multiple film cylinder by a scheme similar to magnetic levitation[5]. In our case the transverse stability is guaranteed while the longitudinal stability is feedback controlled by tracking of the projectile during the acceleration process. We have performed a numerical analysis of our model accelerator based on a realistic mode of operation. We demonstrate trajectory stability in all directions and an acceleration in excess of 10^5 times gravity. An accelerator based on our design will be approximately 1-2 km in length. (See Figure 1), providing a 0.1 g projectile in excess of 1 MJ at the end of our accelerator. We also show the design of the accelerator element, the superconducting solenoid projectile and engineering factors in a realistic construction of the device.

III THE MAGNETIC LINEAR ACCELERATOR (MAGLAC)

To approach the problems of actual accelerator design it's useful to review magnetic levitation. Suppose we want to keep a dipole μ, on the axis of a circular current loop. Let the loop have radius a and carry current I. Let z be the vertical coordinate with z = 0 in the plane of the loop. We use a scalar potential

$$\phi = \frac{\mu_0 I z}{\sqrt{a^2+z^2}} . \tag{3.1}$$

If the dipole is on the z axis with μ vertical, it feels a force

$$F_z = -\mu \frac{\partial B_z}{\partial z} = \mu \frac{\partial^2 \phi}{\partial z^2} = \frac{3\mu \mu_0 I a^2 z}{\sqrt{a^2 + z^2}^5} \tag{3.2}$$

The first requirement for levitation is to balance gravity. If the dipole mass is m,

$$F_z + mg = 0 \tag{3.3}$$

The second requirement for levitation is stability: if the dipole wanders away from the equilibrium point, there must be a force to push it back. Consider first vertical stability. There are two regions of vertical stability: $a/2 < z < 0$, and $z > a/2$. The force itself has opposite sign in the two regions; they are qualitatively different. For example, a superconductor levitated by Meissner effect ("flux exculsion") would be vertically stable for $z > a/2$; an iron object levitated by induced ferromagnetism would be vertically stable at $-a/2 < z < 0$.

But radial stability is also required. In any region not enclosing currents, ϕ must satisfy Laplace's equation. In cylindrical coordinates ($r^2 = x^2 + y^2$)

$$\frac{\partial \phi}{\partial r} + r\left(\frac{\partial^2 \phi}{\partial r^2} + \frac{\partial^2 \phi}{\partial z^2}\right) = 0. \tag{3.4}$$

Then at $r = 0$, $\frac{\partial \phi}{\partial r} = 0$, and by symmetry

$$\frac{\partial^2 \phi}{\partial r^2} = \frac{\partial^2 \phi}{\partial x^2} = -\frac{1}{2}\frac{\partial^2 \phi}{\partial z^2} \tag{3.5}$$

Then, if μ is directed along z.

$$\frac{\partial F_r}{\partial r} = \frac{\mu\, \partial^3 \phi}{\partial r^2 \partial z} = -\frac{\mu}{2}\frac{\partial^3 \phi}{\partial z^3} = -\frac{1}{2}\frac{\partial F_z}{\partial z}. \tag{3.6}$$

The negative sign means radial and vertical stability are mutually exclusive. This is a special case of Earnshaw's theorem. Thus magnetic levitation can be stable either radially <u>or</u> vertically, never both at once. The usual choice is to select radial stability and get vertical stability by feedback from a sensor.

IV ACCELERATOR STRUCTURE (R. Hartung)

By the principle of equivalence, a levitation scheme is an accelerator. But it's not yet useful; the current loop must move with the dipole. No acceleration persists unless we provide a way to accelerate the current loop. If we switch current from loop to loop, we can simulate a loop moving in an arbitrary manner.

For this initial evaluation, we neglect (a) resistance, R, of the loop, (b) reaction from the accelerated object, (c) radiative effects, including "retardation), and (d) mutual inductance between the loops. To avoid having to switch large currents, we drive each loop from a capacitor C, through a diode and a switch. When the switch is turned on, the LC circuit executes ½ period of an oscillation before being quenched by the diode.

In a loop turned on at $t - t_o$, the current is

$I = 0,\qquad t < t_o$ and $t > t_o + \pi\sqrt{CL}$

$$I = I_{max} \sin \frac{t-t_o}{\sqrt{CL}},\quad t_o < t < t_o + \pi\sqrt{CL} \tag{4.1}$$

Here C is the capacitance, L is the self inductance of the loop, and the maximum current, $I_{max} = V_o \sqrt{C/L}$, depends on the initial voltage, V_o. Before presenting results of simulation of this model, we discuss some qualitative features. The dipole tends to line up so as to be sucked into the region of highest field. The opposite case, using Meissner effect, is not considered here.

Then the radial motion will be stable, if and only if the dipole is farther than $-a/2$ behind the peak current. Then z stability (longitudinal) must come from feedback, i.e. the switching on of the current loops must be synchronized with the dipole motion. We assume that an arbitrary trigger function of position and velocity is possible. As a first order proof-of-principle, a crude model has been simulated by numerically integration of a hypothetical accelerator. The simulation parameters are given in Table I. The trigger scheme used was as follows: The loop at position z_o is turned on when the solenoid position, z, and velocity, v, satisfy $z + v \cdot \pi \sqrt{LC} = z_o$. This trigger, which was picked arbitratily, is such that the extrapolated time when the solenoid will cross the plane of the loop, will be the end of the current cycle for that loop. Acceleration functions A_d, are shown in Figure 2a. The focussing function, k/m, of the accelerator is shown in Figure 2b. For $d \leq 1.0$ cm, k/m is always negative, therby providing continuous radial focussing.

V PROJECTILE CONSIDERATIONS (E. Lehman, S. Mahanti)

For any projectile the equation describing magnetic acceleration is

$$\vec{F} = \vec{\nabla}\int \vec{M}\cdot\vec{B}\ dv \qquad (5.1)$$

where $\vec{M}$ is the magnetic dipole moment density and $\vec{B}$ is the external field, the integration is over the projectile volume. The magnetization is related to the internal current density $\vec{j}$ by $\vec{\nabla}\times\vec{M} = -\vec{j}$.

Requirements for the projectile choice include; (i) Interaction with the external field should be large enough to achieve velocities of about 10^5m/sec in a distance of a few km. (ii) Each projectile must have almost exactly the same behavior as every other projectile under the accelerating fields. (iii) A. C. fields are certain to be encountered by the projectile. The projectile must not have its moment destroyed by them. (iv) Other effects, such as collisional heating from residual gas in the accelerator or radiational heating, must not destroy the projectiles moment. (v) The projectile must be easy and cheap to build.

We now discuss different projectile choices. A piece of ferromagnetic material will be drawn into a magnetic field which is stronger than its saturation moment density $\vec{M}_{sat}$ with a force,

$$F = \vec{\nabla}\int_V \vec{B}\cdot\vec{M}_{sat} \tag{5.2}$$

In principle, there appears to be no limit to the acceleration possible. However, for iron the saturation moment corresponds to a field of about 2T. For an external field of 10T and a projectile radius of about 1mm it is found that a projectile energy of 10^6J will require about 10km. Increasing B would shorten this but is difficult.

The inevitable relative motion between the accelerating fields and the projectile will cause eddy currents in the projectile. Let the change of the magnetic field at the projectile be dB/dt, we can define dB/dt = $\zeta v dB/dz$. In the case of a radially constant magnetic field and a cylindrically symmetric projectile with velocity v the ohmic power is given by, (for resistivity ρ)

$$P_{ohm} = \zeta^2 (dB/dz)^2 V/8\rho \times r^2 v^2 \tag{5.3}$$

r is the projectile radius and V is its volume. This leads to a limiting velocity $v_f = 10^5$ m/sec. Even if v_l the, limiting velocity, is equal to v_f, we find ζ is less than 10^{-2}. The total ohmic heat delivered is given by W_{ohm};

$$W_{ohm} = m v_f^2/2 \quad \times 2/3 \; v_f/v_l \tag{5.4}$$

For a final energy of 10^6J and $v_f/v_l = 10^{-1}$, we find that an iron projectile will heat by about 10^4 °K! The temporal uniformity required at the projectile to avoid this, $\zeta < 10^{-4}$, appears prohibitive. For ferrite projectiles ρ is much higher than for iron but the saturation moment density is at least ten times lower. This means that the accelerator would have to be much too long.

Another possible choice is a superconducting projectile. A type I superconductor excludes the applied magnetic field and thus has a magnetization density $\vec{M} = \mu_o \vec{B}$. However, critical fields of order 10^{-2}T rule out these materials.

A type II (hard) superconductor has a much higher critical field. However, the supercurrent density that can be carried is highly sample dependent. For example, if the sample has few lattice defects then only a small supercurrent can be carried in the presence of a large field H ($H_{c1} < H < H_{c2}$). The reason for this is that a type II superconductor is permeated by flux tubes each carrying a unit of flux Φ_o, a fluxon. The fluxons feel a Lorentz force $j \times \Phi_o$ for current density j. This causes the fluxons to migrate and viscous resistance to their motion leads to losses. The flux migration is opposed by pinning forces P_v. In a defect free material P_v is very small so that small j's will cause losses. Defects greatly increase P_v and allow much greater supercurrents. In order to overcome this one purposely makes the lattice poor. In spite of this the maximum j in a bulk sample is only about 10^9amp/m^2. This implies too small a magnetic moment for a 1 km accelerator. In addition, the actual magnetic moment will be strongly sample dependent which presents standardization problems.

Thin superconducting foils wound around a core and supporting a permanent dipole moment seem a promising choice of projectile. The superconducting foils will have very strong pinning forces and thus be able to sustain large supercurrents. Their A. C. properties will also be reasonably good. The A. C. fields will be shielded by the outer layer of superconductor. If ν is the frequency of the a.c. field, h its amplitude, P_v the pinning force and H the D. C. field, the power output of the outer layer is per unit area:

$$4\mu_o Hh^3\ \nu/3P_v\ (W/m^2) \tag{5.5}$$

We can estimate this by taking the D. C. field as 10T, the A. C. field as 0.1T and a pinning force corresponding to a maximum current density of 10^{10} amp/m^2. For a projectile flight time of 10^{-2} sec and $\nu = 10^4$Hz the projectile will heat by about 1^0K. We have made the assumption that the heat in the outer layer is dissapated rapidly in the projectile. Simple consideration based on a diffusion equation for heat flow into the projectile give a relaxation time for a temperature gradient across 1 mm of about 10^{-3} sec. The projectile gains little heat during this time so that it can be regarded in thermal equilibrium during its flight.

A foil projectile can be prepared by winding N layers of foil of thickness T and lenght 1 around a suitable core. The projectile is then placed in a magnetic field and cooled to below its transition temperature. The initial flux is trapped by setting up a magnetization current density j and the magnetic moment μ is given by;

$$\mu = j\pi R^2 N1T\ [1+ (NT/R) + 1/3\ (NT/R)^2] \tag{5.6}$$

Recently large scale production of an Nb_3Sn foil was reported. T is 0.03 mm and experiments in trapping flux gave $j \simeq 10^9$ amp/m^2, limited by the 6T field of the magnetizing magnet.

If we assume that we can achieve current densities of 10^{10} amp/m^2, for N=30 (1mm of windings), R = 1mm and 1 = 3mm, we find μ = .64 amp·m. This should be suitable for a 1km. accelerator (1 is really not relevant as the magnetic field gradient is limited to $2B_c/1$ for B_c the critical field so that the energy gain is independent of 1). It appears that a foil wound projectile with a heat shield (see below) will provide a suitable choice of projectile.

Our final topic in this section is the heating the projectile undergoes during flight. We have already discussed the effects from a.c. fields; two other sources of heating are absorption of radiation from the accelerator walls and inelastic collisions with the residual gas in the accelerator tube. To estimate the radiational heating we take the accelerator walls at a temperature T_a and the projectile at $T = 0$. For a projectile of surface area A energy is absorbed at a rate;

$$dE/dt = \frac{8\pi}{3} \ A\pi^4 h/15c^2 \quad (k_B T_a{}^4/h) \tag{5.8}$$

For our projectile with a specific heat of about $1 J/kg^oK$, we find a heating rate of 1 $^0K/sec$ with $T_a = 10^2 \ ^0K$. Radiational heating can thus be ignored for our flight time of 10^{-2} sec.

Collisional heating will be much more severe. If we assume that the air molecules are at rest relative to the projectile, that they have a density ρ and that the cross-sectional area of the projectile is A, we find a heating Q given by

$$Q = 1/8 \ \rho A v_f{}^2 t \tag{5.9}$$

In the above v_f is the final projectile velocity and t is the transit time. We have also assumed perfectly inelastic collisions between the projectile and the gas. For $v_f = 10^5 m/sec$ and $t = 10^{-2}$ sec we find that a temperature rise of 10^oK occurs if ρ is as big as $10^{-14}\rho_{STP}$. This vacuum requirement seems impossible to meet, however, we can avoid it by using a heat shield (which can be molded with the core). With a heat shield we only need about $\rho = 10^{-8}\rho_{STP}$. We are confident, then, that the heating problem is tractable.

VI ACCELERATOR ENGINEERING FOR MAGLAC (G. Plamp)

A preliminary design of the MAGLAC enclosure has been made. Main feature include considerations in cooling vacuum chamber, cryogenic feed through and power delivery. Figure 4 shows a typical section (∿ 1/100) of the accelerator. The power input calculations for this design has been made in Section VII. A cross section of the accelerator element is shown in Figure 5.

Most of the elements are commercially available. Since we expect to have large voltage between individual plates, considerable amount of care would be needed to construct these sections. We do not believe these designs are optimized as yet. Much work is still needed.

VII. POWER INPUT CONSIDERATIONS (B. Dougherty)

In order that the projectile support current desities over $j = 10^9$ A/m^2, and that dissipative losses be reduced in both the projectile and accelerator coils, cryogenic conditions must exist. To achieve this, cooled super (preferably inert) gas circulates around the coils and dielectrics in every accelerator section. Coaxial return lines (see cross-section) provide economical, uniform, additional cooling. Studies of comparable transmission lines[6] indicate that, with far-end expansion and return, one refrigeration/pumping station is adequate to maintain minimal temperature gain along the two kilometer accelerator. Also, three cooling lines, bored through the dielectric with regular disk-shaped adjoining spaces seem sufficient, resulting in a slight parabolic temperature rise ($\leq$ 1°K) near the center of the accelerator.

Heat loss via radiant transfer and gas convection is significantly reduced by using evacuated multi-layer insulation (such as aluminum coated mylar). Conduction through the accelerator sides is then on the same order as that lost through the metallic vacuum leads.

Ohmic heating within the cryogenic envelope is significant only in the electrical power terminators ending each section. Here, losses on the order of one percent of the diverted power, or around 10^4 watts, are encountered for the entire system.

Gas leaks and vibrations are negligible, as are the storage/supply requirements for the refrigerant. Altogether, total losses of nearly 1.5×10^4 Joules are expected for each pulse.

Cool down costs are harder to approximate, since it is difficult to predict the frequency with which this machine will require repair. Conservative estimates[7], however, indicate a crude value of around 10^{10} Joules necessary for every cool down, resulting in an equivalent operational loss of nearly 2×10^4 watts, comparable to cryogenic losses.

The refrigerant is gaseous helium at 6 - 10° K and 15 atmospheres feeding pressure. Higher temperatures jeopardize the projectile superconductivity, leading to possible disastrous heating due to increased resistivity.

As an additional benifit received when operating at low temperatures, material strength characteristics of the projectile and coils are altered enabling them to withstand the high outward magnetic pressure accompanying each current pulse. Also, temperatures below 77°K may improve the vacuum encountered in the flight path by transforming the two kilometer inner tube into an effective cold trap.

Vacuum loss itself is trivial, requiring only about 10^4 watts input for each one percent loss per minute along the entire length of the machine. Individual pumping stations at every accelerator section are used. Vacuum on the order of $< 10^{-8}$ Torr is expected.

Electrical input, on the other hand, is relatively large. Various spark-gap switches have quoted loss rates from 2 to 15 percent of the input power. Terminations for each LC accelerator section loose this same order of energy, provided a 90% recovery rate is maintained through use of storage capacitor banks. Other switches and recycling mechanisms are available, however, and it is expected that the full scale system will be appropriately engineered. Nevertheless, total losses of approximately 10^7 Joules per pulse may be realistic.

Other costs (true costs, converted through typical price estimates and present consumer markets) include downtime and repair. This, again, is hard to predict. However, downtimes from one hour to ten days at an average cost of 10^5 dollars, once a month, for switch repair of LC section replacement lend a total equivalent loss rate of around 5×10^4 watts operational cost.

Even harder to estimate is the projectile production and delivery costs. Assuming a conservative one percent efficiency and ten cents per pellet, we find an equivalent "loss" of nearly 5×10^4 watts. This is comparatively small, and represents double counting anyway, in that this cost is taken out of ultimate fusion delivery rates, and so will be ignored here for the sake of overall efficiency predictions.

All input sources and magnitudes are tabulated in Table II. It is evident that electrical losses constitute the majority of input, so much depends upon actual recovery rates and switch efficiency. Cryogenic and other losses are quite tolerable and sensitive, again, to operational frequency of repair. (We might note that by removing cryogenic needs, i.e. operating at room temperature, total power input remains about the same due to increased resistivities, but useful lifetimes of materials are dramatically reduced because of the accompanying heating.)

Assuming that 10^6 Joules of usable energy are got in every pulse, then, we find an overall efficiency of Q = 5 - 11%.

VIII. MAGLAC ACCELERATOR CONTROL AND POWER CONDITIONING

(J. E. Siebert)

Essential to the operation of MAGLAC is the maintenance of the dipole projectile within the transversely stable region of the propagating magnetic wave. This can be accomplished by achieving proximate longitudinal regulation through feedback-controlled sequential excitation of the accelerator sections. Hence, the dipole can be radially focussed to controllable degree along its trajectory. Clearly, optimization of the tradeoff between projectile acceleration and the strength of transverse focussing is necessary to minimize accelerator length for a given final velocity. The accelerator control system design must support the evolution and tuning of control strategies and accomodate system refinements.

Projectile arrival at discrete locations along the accelerator can be detected optically by fast PIN photodiode response to a laser light obscuration. These indications along with the elapsed time can serve as principle input parameters to a real-time numerical model. Since control actions need only occur at $\sim$ 100 μs intervals, implementation may take the form of a real-time computer-based controller. The attendant advantages of programmable control include the desired adaptability mentioned above along with the facilitation of development, implementation, operation, diagnosis, and maintenance.

As shown above, projectile acceleration will result from large $|dI/dt|$ on the pulse trailing edge. The required line excitation is then the delivery of a pulse of sufficient energy and fall-time to strongly accelerate the projectile. The scheme depicted in Figure 6 employs a capacitive store, a fast triggered switch(s), and a subsystem to recover the remaining wave energy at the end of that accelerator section. Alternative implementations of these subsystems are currently being explored. Especially interesting are the prospects of implementing the capacitive store in charged parallel-connected transmission lines whose lengths are half the desired pulse width, and employing fast opening switches recently reported[8,9] to achieve large dI/dt. The inefficiency of crowbar circuits prohibits their use here.

The capacitive store and switch combination must provide the following:

Pulse Voltage	:	25-75 kV
Peak Current	:	160-400 kA
$\|dI/dt\|$	:	$>10^{12}$ A/sec
Jitter	:	<10 nsec
Repetition Rate	:	1-3 pps
Pulse Energy	:	$\sim$10 kJ/pulse
Life	:	$>10^{8}$ pulses without maintenance

Of all the requirements, the component lifetime will be the most difficult to achieve. This requirement arises from reliability and practicality considerations for a useful fusion reactor.

IX. CONCLUSIONS AND RECOMMENDATIONS

Concepts and design parameters for a magnetic linear accelerator capable of accelerating a 0.1-1.0 gm superconducting projectile (multiple film layer or solenoid) to a velocity exceeding 10^5 m/s are presented. Such a device could conceivably serve as an ignitor for inertial confinement fusion. In contrast to other options for macroscopic particle acceleration, we propose a magnetic linac in which the longitudinal acceleration elements are individually controlled while transverse and rotational motions are inherently stable. This approach is an extension of the well-known method of magnetic levitation. Accelerator and projectile elements are described. Longitudinal and radial stability analysis indicate no obvious obstacles within the current technological state-of-the-art.

None of the considerations of this work indicate any intrinsic limitations. A superconducting linac certainly can be constructed with a modest cost.

We are now entering a situation in which some future substantive theoretical and experimental work should now be supported. These include, for example,

1. Further material research on superconductors under high magnetic field and high frequencies.
2. Theoretical and experimental designs of MAGLAC. Optimization of accelerator designs.
3. Construction of elementary section of MAGLAC.
4. Properties of projectile under traveling wave acceleration.
5. Engineering design of projectiles.
6. Projectile-target interactions.

Perhaps in the near future we could see generation of fusion power in this promising approach as shown in Figure 7.

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TABLE I. Typical Accelerator Parameters

a	radius of loop	0.01 m
d	separation	0.015, 0.01, & 0.004 m (see graphs)
L	inductance of loop	10^{-8} H
C	capacitance per loop	0.7 μF
V_0	applied voltage	20 kV
$\tau =$	$\sqrt{LC}$	84 ns
I_{max}	peak current	170 kA
v	initial velocity of dipole	1 km/s
m	mass of dipole	0.1 g
μ	moment of dipole	1 A•m^2

TABLE II. Overall Input

Source (entire system)	Est.'d Magnitude (Joules/projectile)
Cryogenics	$\sim$ 1% efficiency
Elec. heating	
capacitors	20
leads	50
noise	10
terminations	$\lesssim 10^4$
Heat transfer	
conduction	3×10^3
radiation	nil
convection	10
Miscellaneous	
cool down	$\sim 2 \times 10^4$ (equivalency)
absorption	nil
gas leaks	20
vibration	nil
refrigerant production & storage	nil

Source (entire system)	Est.'d Magnitude (Joules/projectile)
Vacuum	$\sim$ 1% efficiency
Maintainence	$\gtrsim 10^2$
Initial evacuation	nil
Electrical	$\gtrsim$ 80% efficiency
Switches	$\sim 5 \times 10^6$
Leads	$\sim 3 \times 10^3$
Terminations (90% recovery)	$\gtrsim 4 \times 10^6$
Other	$\sim 10^2$
Other	(equivalency)
Downtime	$\sim 4 \times 10^5$
Repair	$\gtrsim 5 \times 10^3$
Total input	$\sim (1.4 \pm 0.5) \times 10^7$ J

CONCEPT OF MAGNETIC ACCELERATOR

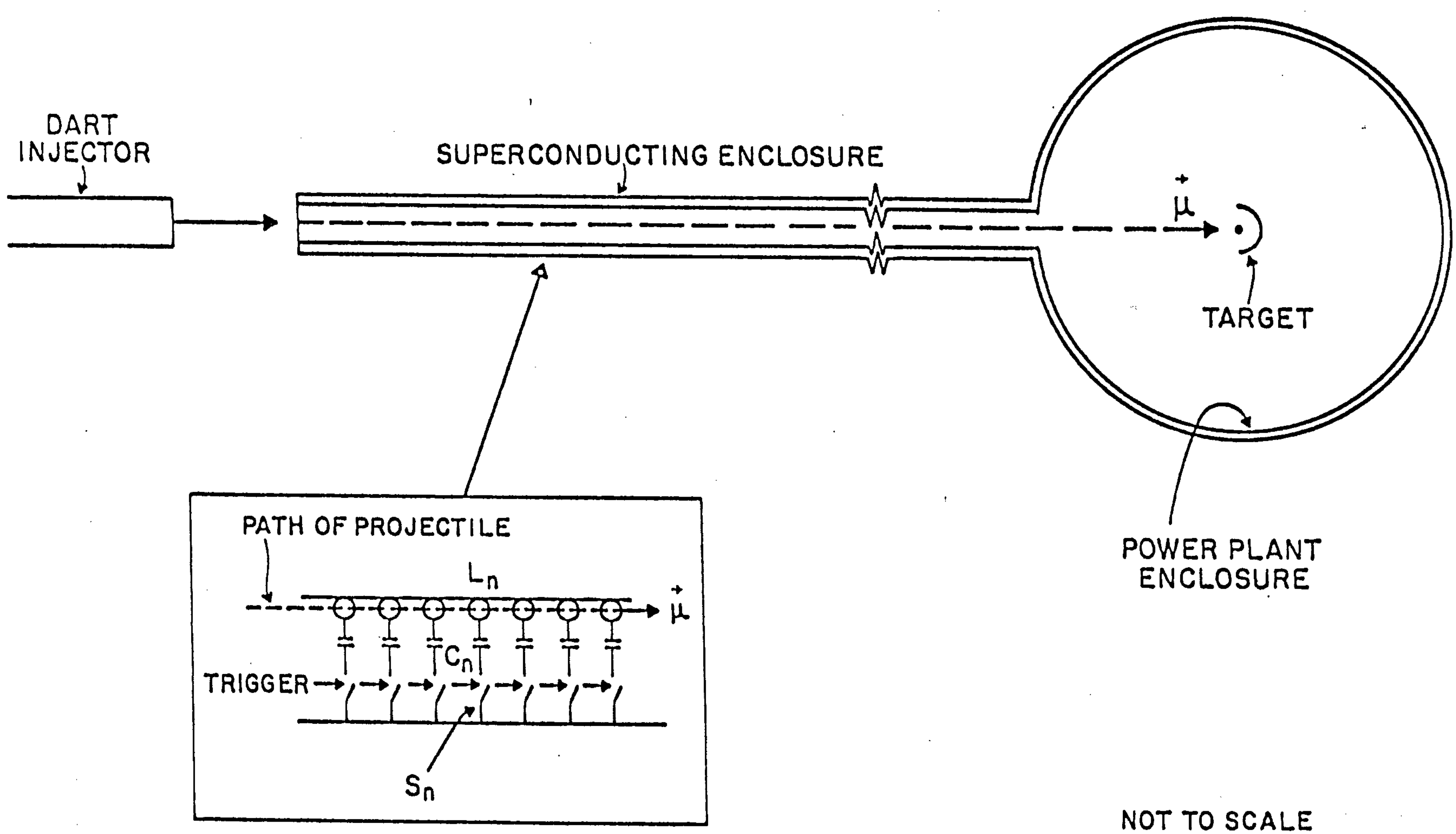
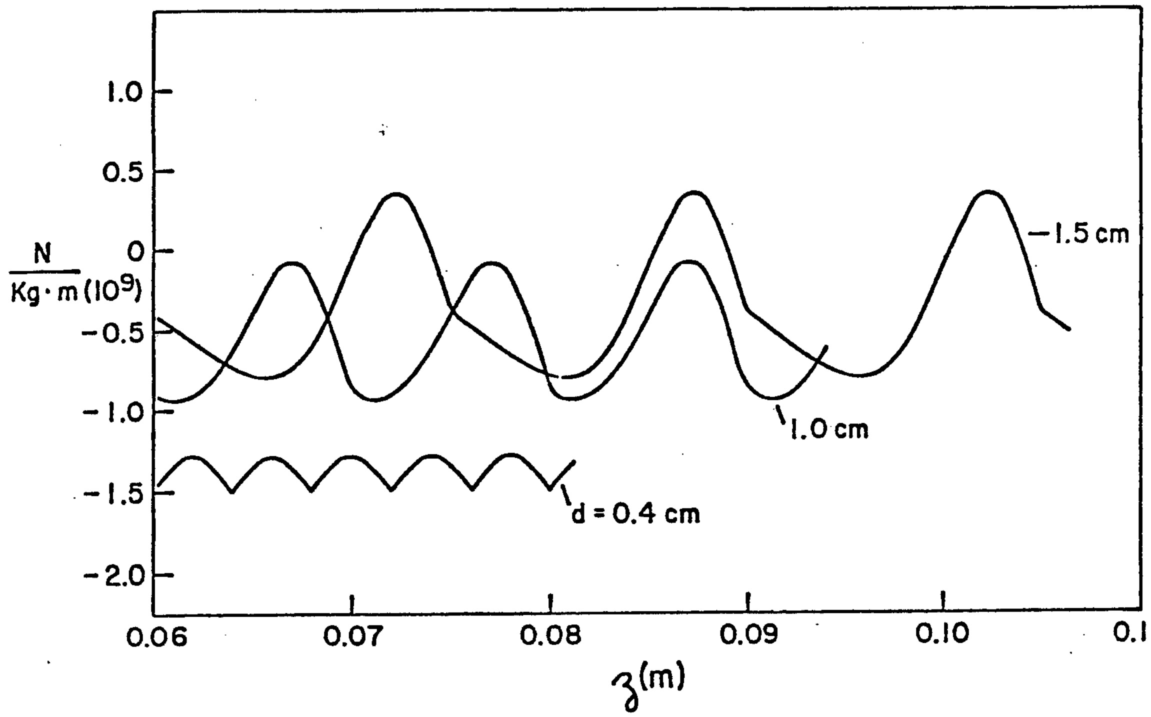
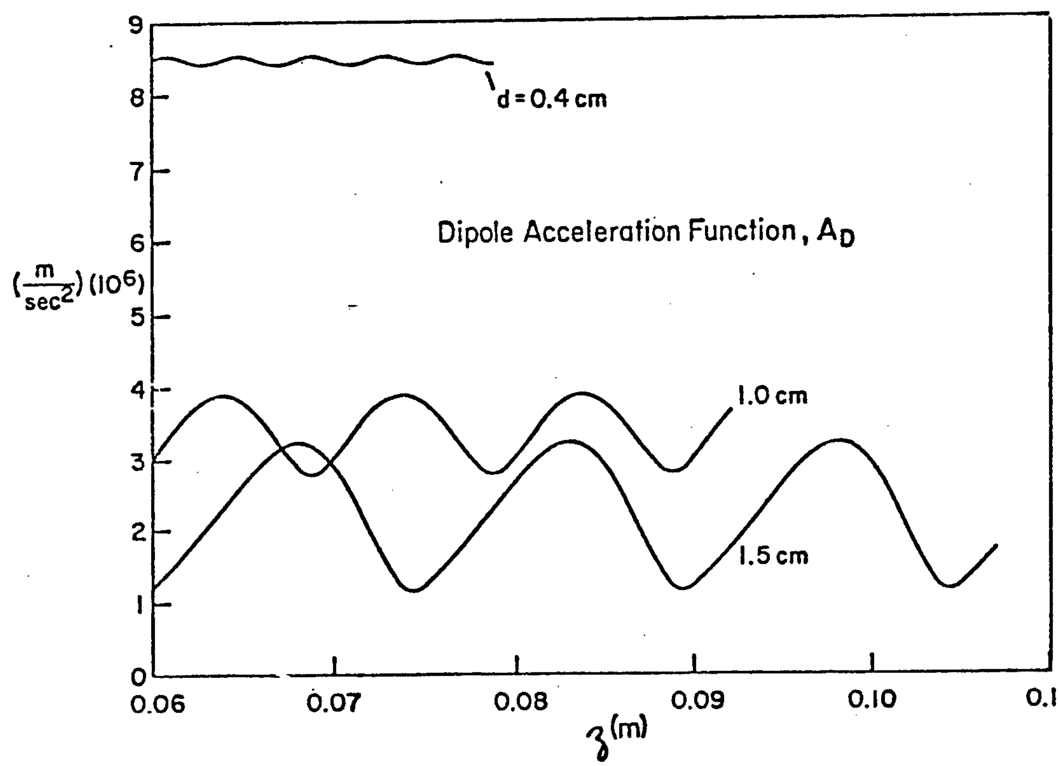


FIGURE 1.



(b)

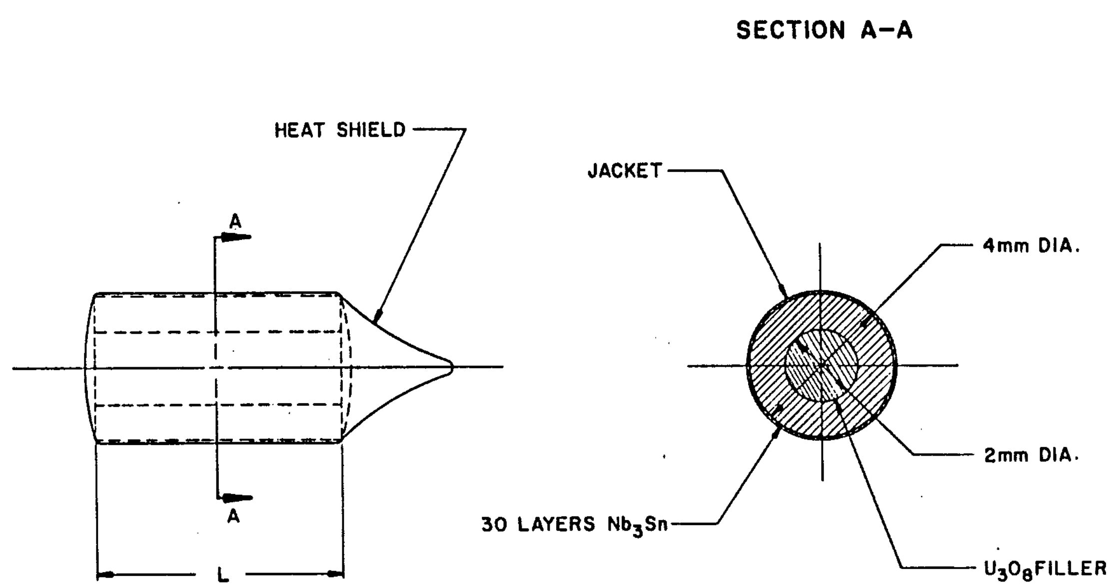


(a)

FIGURE 2(a,b).

PROJECTILE (THIN FOIL DESIGN)

PROJECTILE



L– INDICATES THE LENGTH OF THE PROJECTILE WHICH IS SEVERAL MILLIMETERS LONG

FIGURE 3.

LABORATORY FOR IMPACT FUSION		
SCALE: 13/1 DATE: 6/10/79	APPROVED BY: Dr. K. W. CHEN	DRAWN BY G.H.P.
MICHIGAN STATE UNIVERSITY		
		PR-1000

MAGNETIC LINEAR ACCELERATOR (MAGLAC) SECTION

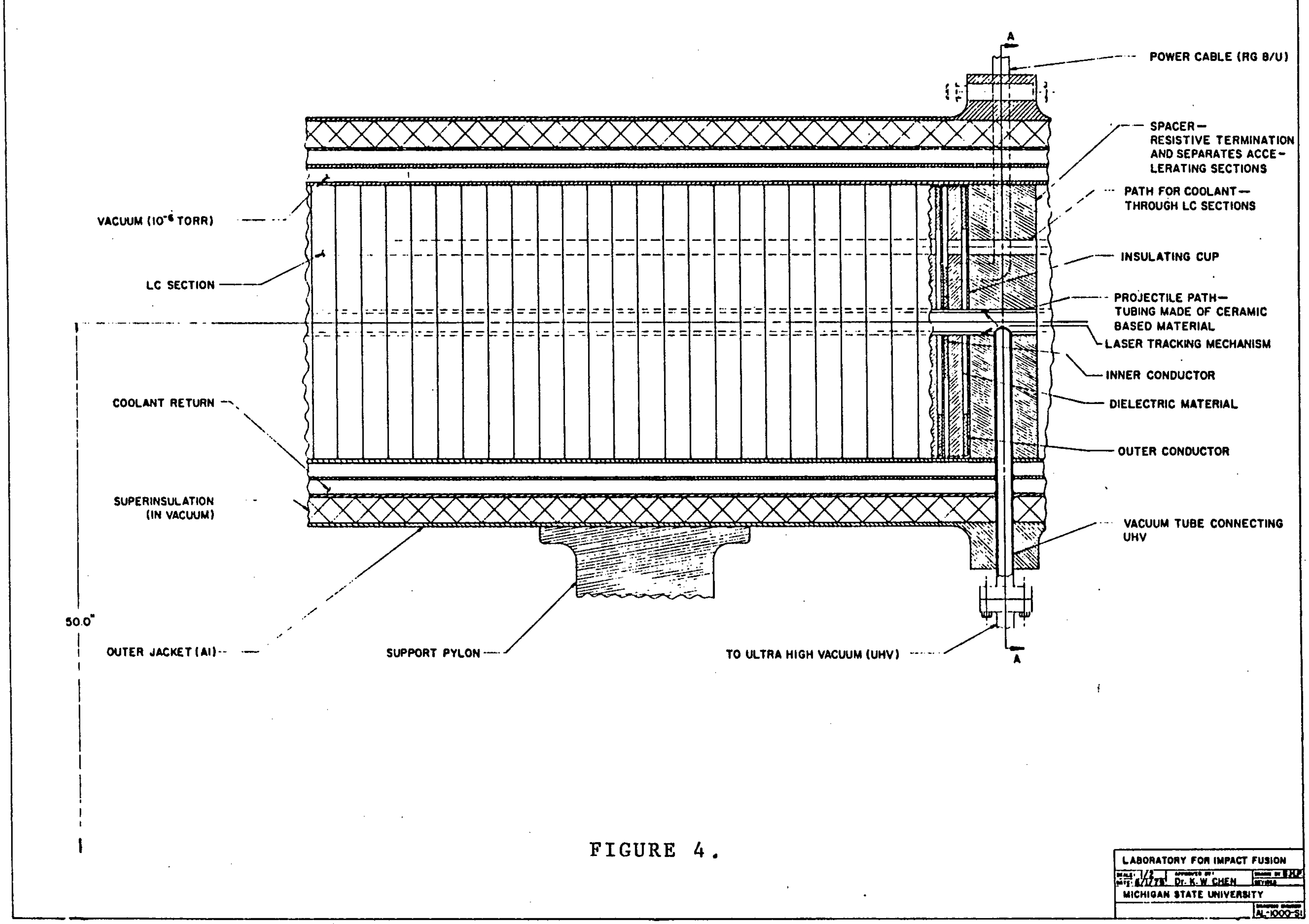


FIGURE 4.

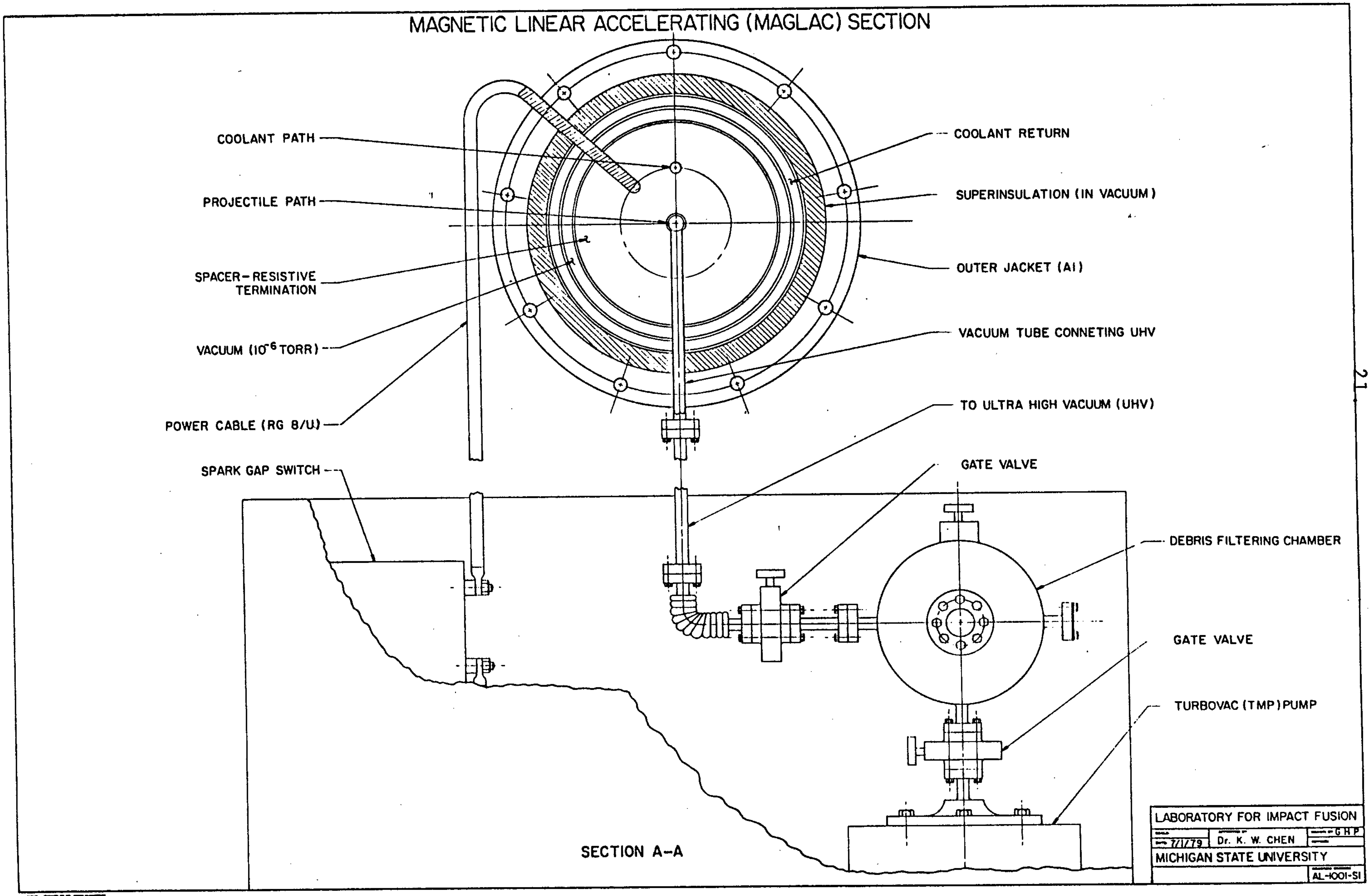

MAGNETIC LINEAR ACCELERATING (MAGLAC) SECTION
COOLANT PATH
PROJECTILE PATH
SPACER-RESISTIVE TERMINATION
VACUUM (10^{-6} TORR)
POWER CABLE (RG 8/U)
SPARK GAP SWITCH
COOLANT RETURN
SUPERINSULATION (IN VACUUM)
OUTER JACKET (Al)
VACUUM TUBE CONNETING UHV
TO ULTRA HIGH VACUUM (UHV)
GATE VALVE
DEBRIS FILTERING CHAMBER
GATE VALVE
TURBOVAC (TMP) PUMP
SECTION A-A
LABORATORY FOR IMPACT FUSION
7/1/79
Dr. K. W. CHEN
GHP
MICHIGAN STATE UNIVERSITY
AL-1001-SI

FIGURE 5.

POWER CONDITIONING FOR A SINGLE ACCELERATOR SECTION

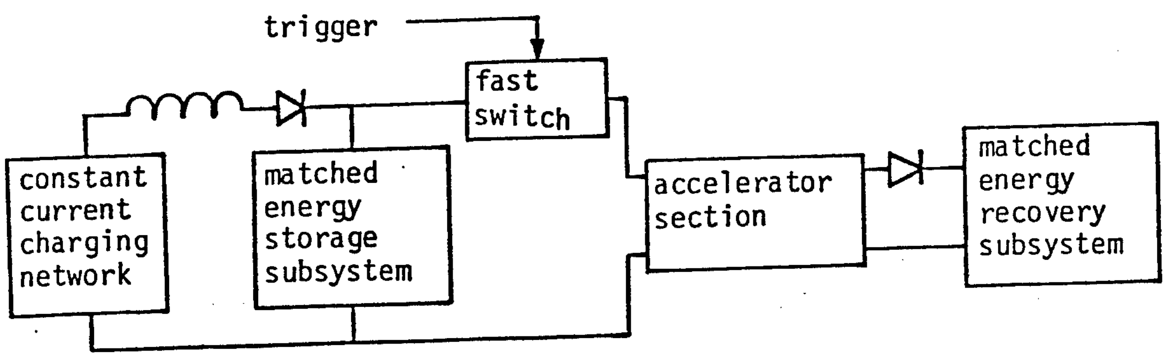
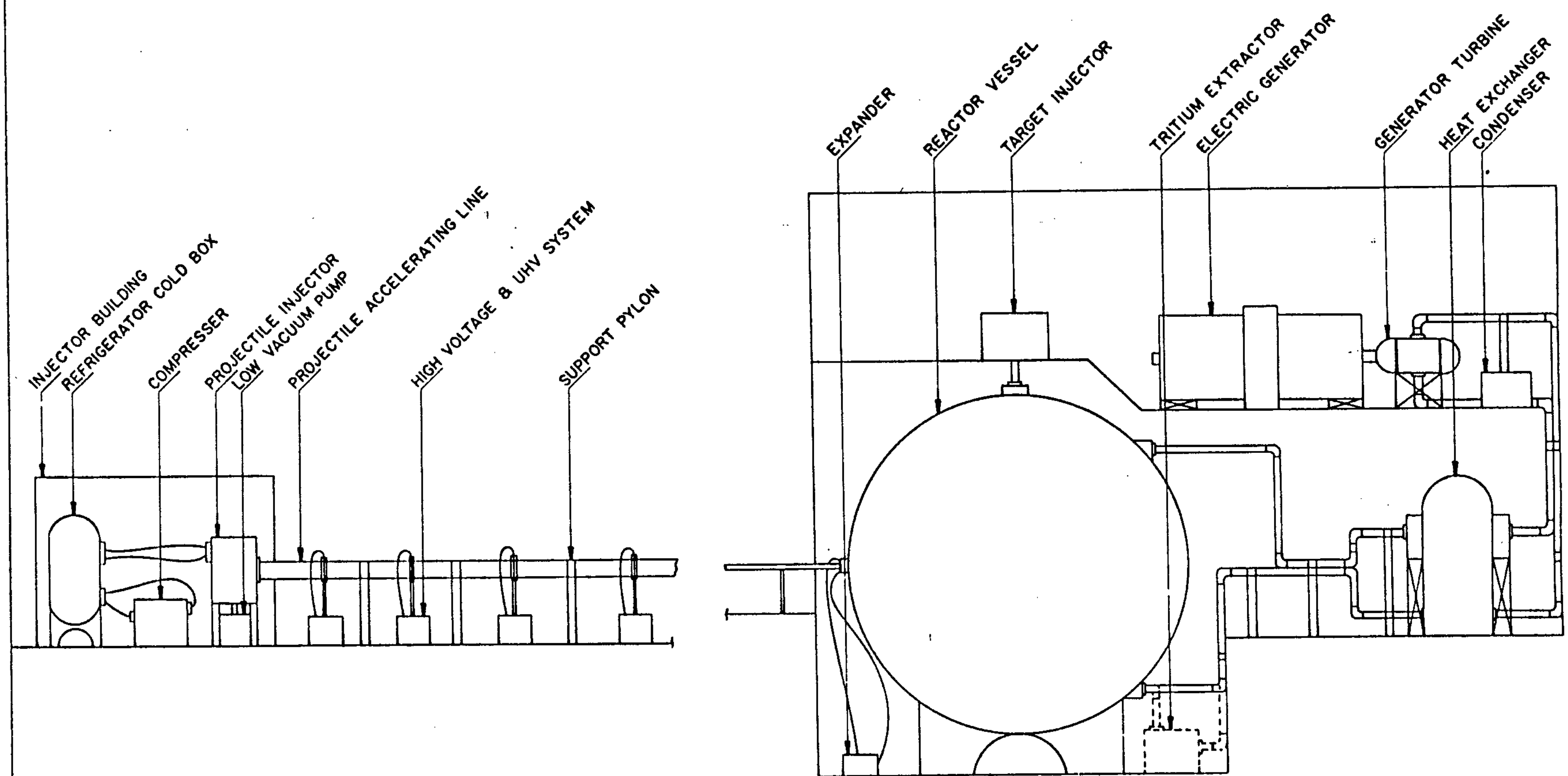


FIGURE 6.

Power Conditioning For A Single Accelerator Section

INJECTOR AND ACCELERATOR LINE

POWER STATION (ENLARGED VIEW)



INJECTOR AND PROJECTILE LINE

POWER STATION
(ENLARGED VIEW)

FIGURE 7.

LABORATORY FOR IMPACT FUSION
SCALE
DATE 6/7/79
APPROVED BY Dr. K. W. CHEN
DRAWN BY J.G.L.
REVISED
MICHIGAN STATE UNIVERSITY
DRAWING NUMBER PS-1000